Prototyping of a neutron veto for SuperCDMS

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Abstract

We seek to answer many of the questions open in the design process for a neutron veto for the cryogenic dark matter search (CDMS). These include what materials should be used to build the veto, what glues should be used in which situations, which fluors to use in the scintillator, and how silicon photomultipliers (SiPMs) can be used as light detectors for the veto. The SiPMs required careful study because they are an emerging technology. We found that SiPMs have a region in which their photon detection is mostly linear, which allows them to be used for the purposes of a veto due to low light levels produced. An analysis of what makes them nonlinear, such as crosstalk, afterpulsing, and dark noise is included in the research.

I. MOTIVATION

CDMS is one of the leading experimental searches for dark matter. The experiment is designed to operate at cryogenic temperatures and detect dark matter particles directly. These dark matter particles, called weakly interacting massive particles (WIMPs), are expected to interact with the detector crystals via nuclear recoil. The next generation, SuperCDMS, will be located two kilometers underground to shield from most common source of radiation on the surface; cosmic rays. The detector will still need other shielding, one layer of which is a neutron veto.

Neutrons also interact with the detector's germanium and silicon crystals via nuclear recoil, so a neutron hit in the detector would be almost impossible to distinguish from a WIMP.[1] This means neutrons have to be handled differently than other backgrounds that would interact with the electrons instead of the nuclei. The other backgrounds can be handled with yield discrimination and other discrimination methods[2], but the neutron veto must detect and absorb neutrons as a separate step. The veto will be a liquid scintillator detector built in modules of acrylic tanks surrounding the dark matter detector cryostat. The scintillator should be able to capture neutrons and produce light to be captured by wavelength shifting fibers and then detected by SiPMs. The research this summer was dedicated to building and testing a 1/4-scale prototype of a single module of the neutron veto using a liquid scintillator to test the effectiveness of certain fluors, glues, and processes for making the detector and procedures concerning SiPMs.

II. LINEARITY OF SIPMS

An initial task was to determine whether SiPMs exhibit linearity of photon detection; that is, whether there is a linear relationship between the number of photons actually hitting the SiPM and the current response in the SiPM. A main problem in SiPMs is a phenomenon known as crosstalk. Crosstalk happens when a photon is created in the avalanche of a pixel and that photon escapes and triggers an avalanche in a neighboring pixel. This means that for an event with a single photon, the detector may display that two or more were detected. Another phenomenon contributing to nonlinearity is afterpulsing, where the SiPM will detect smaller pulses in a pixel after the initial avalanche. These pulses are smaller because they occur during the time that the initial avalanche is being quenched.

Since photomultiplier tubes (PMTs) are known to be linear, we compared SiPM response to PMT response when both were exposed to a flashing LED. We placed the SiPM and PMT in a dark box with an LED in view of both detectors. After closing the dark box, we set the LED to flash through a sequence of brightnesses, so we could observe the responses of both detectors at various numbers of photons. If the SiPM is linear, we should see a line, meaning that there is a direct relationship between the response of the SiPM and that of the PMT and thus the actual number of photons. At small numbers of photons (under approximately 50), we found that SiPMs can be approximated as linear. The more light they receive, the less linear they become due to increased probability of crosstalk and afterpulsing, and at a certain amount of light, saturation effects will take over because the SiPM only has a finite number of pixels. This can be observed in Figures 1 and 2.

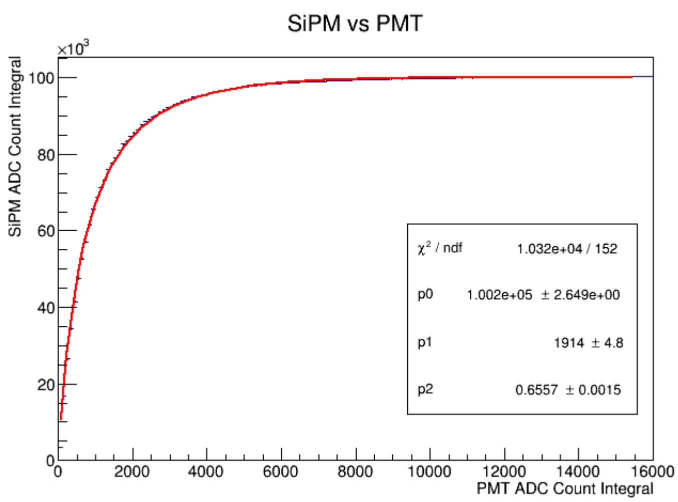

FIG. 1. Saturation can be seen in the flattening of the curve at higher amounts of light. ADC count is proportional to the number of photoelectrons, which should be proportional to the amount of light received if the detector is linear. We could not find a function that fit this trend.

III. TEMPERATURE STUDIES OF SIPMS

Temperature affect SiPMs due to their semiconducting properties, so we studied the gain, dark rate, and photon detection efficiency at various temperatures. The SiPMs were mounted to aluminum plates with internal channels for cooling liquid to flow through. These plates

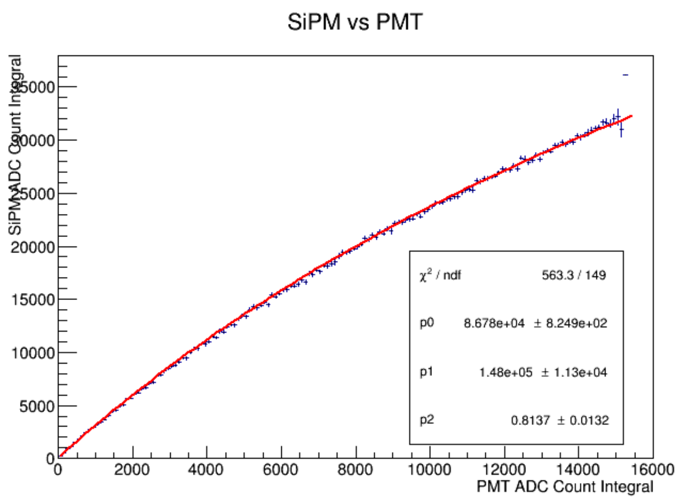

FIG. 2. Approximate linearity in low numbers of photons.

were connected to a chiller, which could be set to cool the liquid to whatever temperature we like. All temperatures given refer to the temperature of the liquid in the chiller. The SiPMs were consistently at slightly higher temperatures than the chiller because they are not well thermally connected to the cooling plates.

A. Gain

The gain of a SiPM is the number of electrons produced in the avalanche. If more electrons are produced, more current is produced and it is easier to see that a photon was detected. Most of the gains we measured were in integrated ADC counts; that is, the analog-to-digital converter's count of charge which is directly proportional to the actual number of electrons. We calculated the gain by plotting a histogram of the integral of each event's trigger window like the one in Figure 3 and calculating the distance in ADC counts between neighboring peaks, which represent individual photons. The ADC count between peaks is proportional to the gain.

We know that gain is also dependent on the bias voltage at which the SiPMs run. By keeping the SiPMs at a constant temperature and varying their bias voltage, we produced curves of gain vs. bias voltage like the one in Figure 4, which shows a nice linear trend between gain and bias voltage.

We started off at the bias voltage for room temperature given on the SiPM packages by

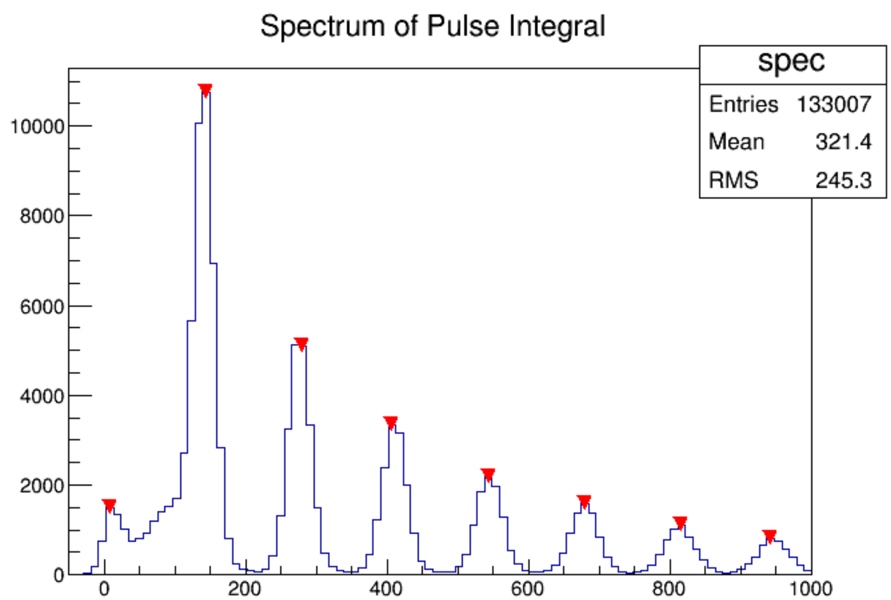

FIG. 3. Well-separated peaks for multiple photons.

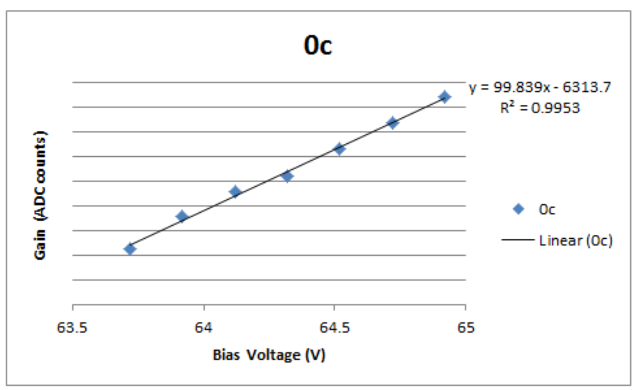

FIG. 4. Gain vs. bias voltage line for 0 °C, an example of the type of linear relationship we get upon varying bias voltage.

Hamamatsu. This operating voltage is nominally 1.4 V above the breakdown voltage where no photons would be detected. We recorded a run of the SiPMs detecting light from the LED set at a constant brightness, then turned the bias voltage down by 0.2 V and took another run. This was repeated until we no longer saw photons being detected. We then turned down the temperature of the chiller and let the SiPMs come to an equilibrium temperature, then took another set of runs in the same manner. This was done for temperatures of 20, 10, 5, 0, -5, -10, and -20 °C. We then produced the plot in Figure 5, showing the trend of increasing gain with decreasing temperature at constant bias voltage; it also shows that to keep a fixed gain between two temperatures, the bias voltaged must be changed. This was all done before the SiPMs, and their cooling plates were attached to the detector box and wavelength shifting fibers.

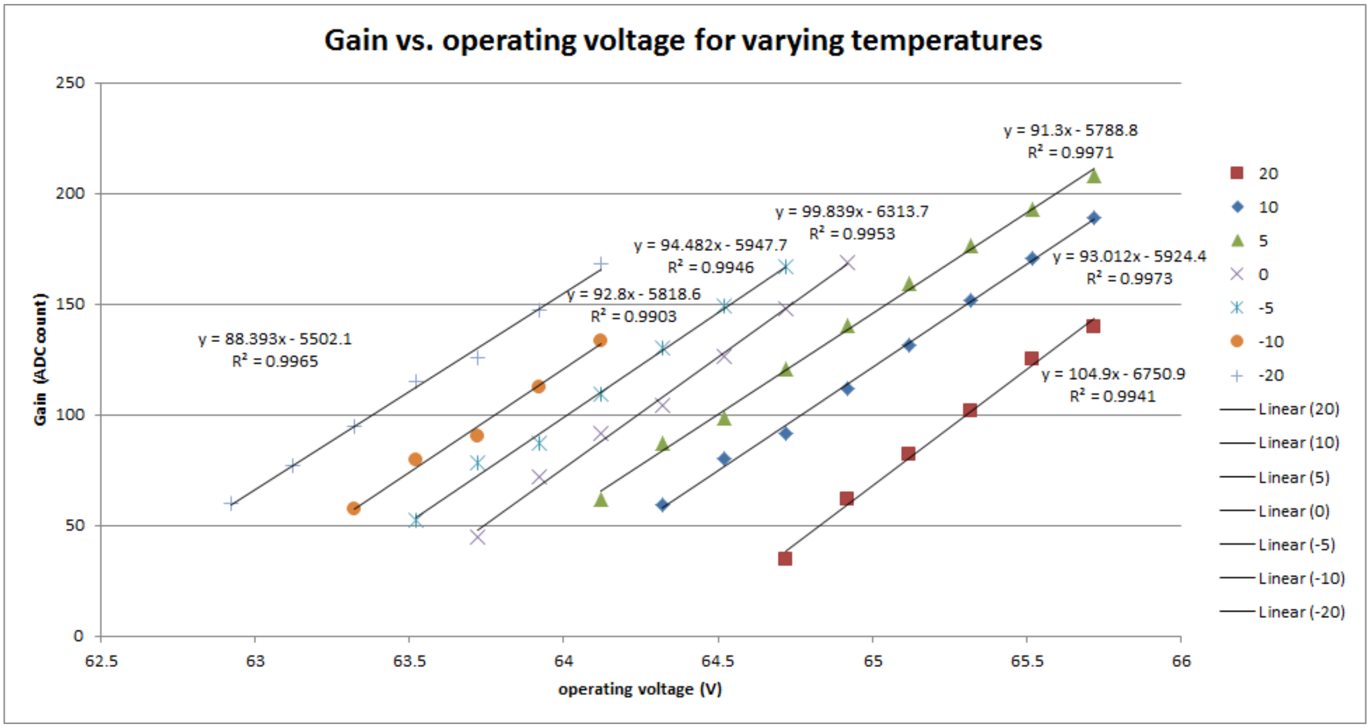

FIG. 5. Gain vs. bias voltage for the various temperatures. Using these fits, we can decide on an optimal gain and use the fit for the temperature we want to use to find the required Vbias.

B. Dark noise

Dark noise occurs when the SiPM produces an avalanche withoutthe presence of a photon. It may detect a thermal electron, or some other source of noise. We know that dark rate should decrease with temperature. Using the same data gathered in the manner described in the gain section, we were able to do a simple analysis of dark noise with respect to temperature. A program searched through the 100 000 recorded events for each run and counted the number of events with a pulse in the time before the LED was known to have flashed. This number was plotted with respect to temperature in the graph in Figure 6, and equation 1 was fitted to it.

$$N = A * T^{1/2} e^{-\alpha T} \tag{1}$$

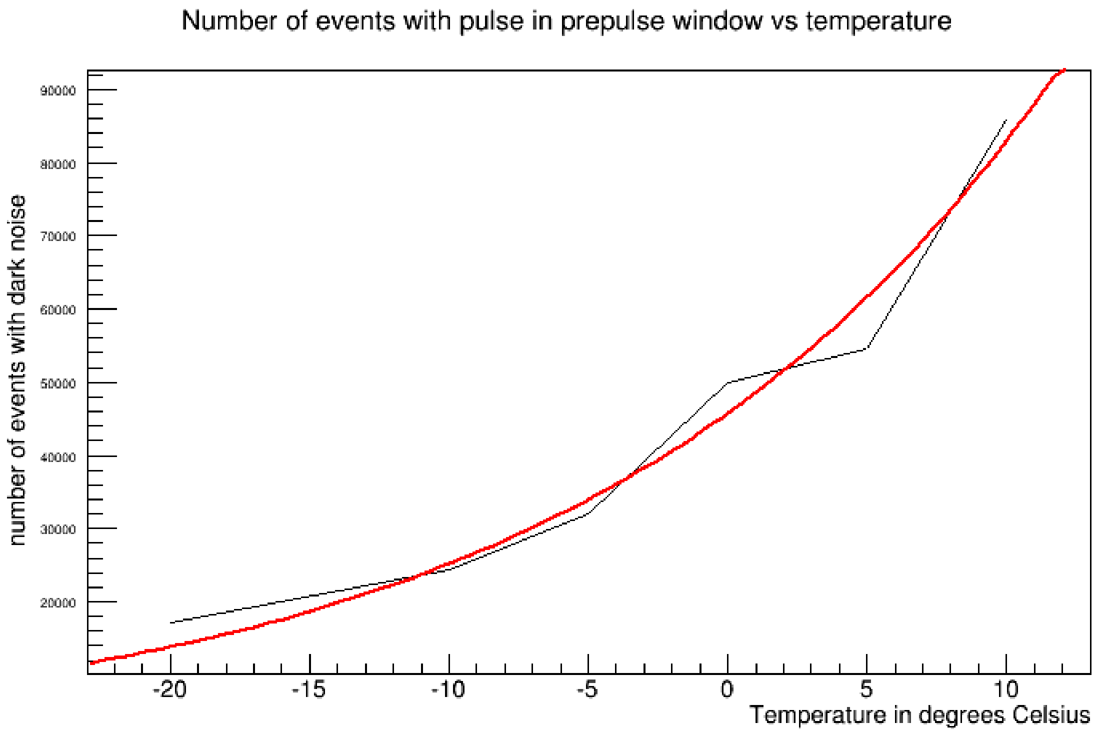

FIG. 6. Exponential trend of number of pulses detected in the prepulse window with temperature. Lower temperatures are better for reducing the dark rate.

IV. THE BOX

The detector prototype itself is made of six pieces of 1/2-inch-thick acrylic lined with Lumirror reflector. The acrylic is held together with a water-thin solvent designed to "weld" acrylic. This left some gaps that were sealed with a thicker acrylic cement. We found that the best way to seal all leaks was to cut a channel in the acrylic sections at the seam and fill the entire edge with thick acrylic cement.

There are two ports on the box for filling with the liquid scintillator and for an expansion volume. Sixteen wavelength shifting fibers are stretched through the box in four groups of four. Each end of each group of four fibers is guided to the photosensitive surface of one of eight SiPMs through holes in the cooling plates to which the SiPMs are attached. Images of this setup are shown in Figures 7 and 8. An insulation box is fitted around the SiPMs to keep them cold. One set of fibers was bent and maybe broken during assembly. As we were putting the lid on the box, it was dropped into the box onto a set of already glued fibers. These fibers have exhibited at least some lit loss in an initial test.

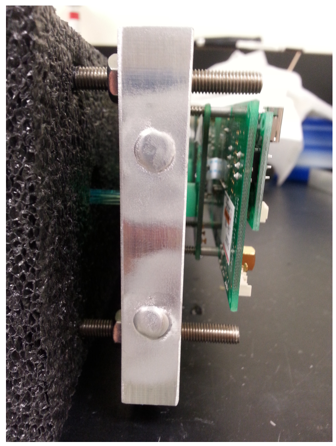

FIG. 7. The fibers seen passing through the cooling plate attached to SiPMs.

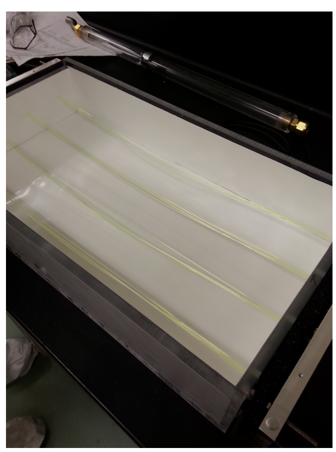

FIG. 8. The sixteen wavelength shifting fibers seen in the detector box before the lid was attached.

This detector box sits inside a secondary containment box which doubles as a dark box. Each SiPM is connected to the CAEN V1720 data acquisition system and a power supply through ports in this secondary containment box, as seen in Figure 9.

FIG. 9. The detector seen inside the secondary containment box, with the lid off.

V. SCINTILLATION COCKTAIL

One of the first tasks was to decide which secondary wavelength shifter to put in the scintillator. It was already decided that the base should be linear alkylbenzene (LAB), the primary fluor would be PPO[3], and that trimethyl borate (TMB) would be used for neutron capture. Our task was to find out which fluor would shift the wavelength of the scintillation light closer to the ideal absorption range of the wavelength shifting fibers. The ideal absorption wavelength of the Kuraray Y11 wavelength shifting fibers is around 440 nm.[4] PPO's emission peaks at 360 nm, so the best choice for the secondary wavelength shifter was bis-MSB, which absorbs around 350 nm and emits at around 440 nm.

It was then necessary to determine the ideal ratios to be put in the scintillator. We did this experimentally by mixing a few samples. We mixed a master batch of 2g PPO per liter of LAB, which was the accepted ideal concentration. We then mixed a batch with the 2g/L PPO plus a 65 mg/L of bis-MSB. These two mixtures were then used to create samples with varying amounts of bis-MSB in bis-MSB:PPO mix ratios of 1:1, 1:4, and 1:9. We then used a fluorimeter to measure the emission of each, plus the fluorescence of the LAB and master batches, to determine which was best for our purposes. We found that the 1:9 mix, which is 2g/L PPO and 6.5 mg/L bisMSB, best matched the absorption spectrum of the fibers. This is demonstrated in Fgure 10. The final mixture of liquid will be 30% TMB and 70% scintillation cocktail as described above, by mass.

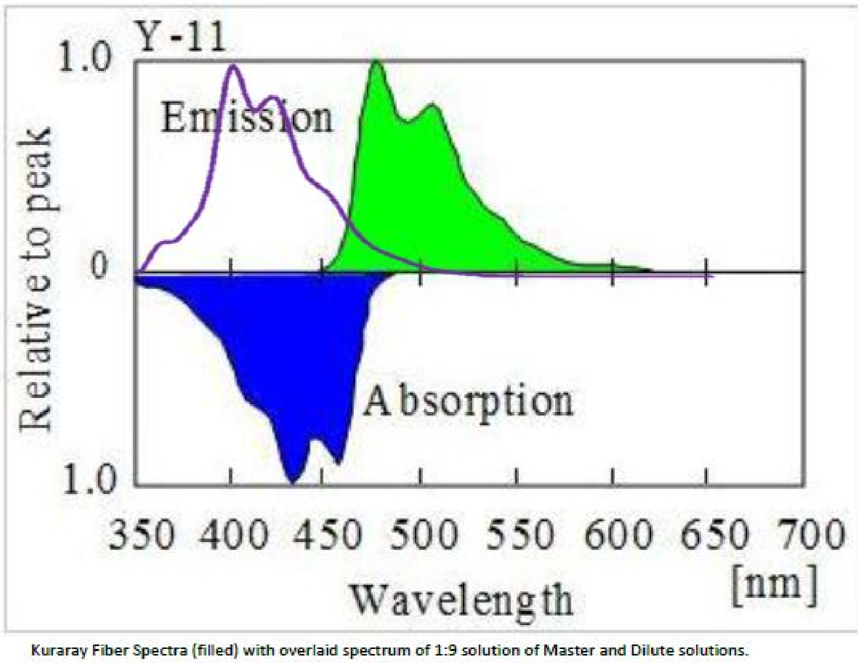

FIG. 10. An overlay of the emmission spectrum of the 1:9 mix (in purple) on the absorption spectrum of the wavelength shifting fibers (in blue). Note that the heights on the spectra are not normalized to the same relative intensity, so only the wavelengths at which peaks occur are being compared.

VI. TRIMETHYL BORATE'S DIFFICULTIES

Since the this detector is being built out of relatively new technologies and materials, we need to pay attention to even the smallest details of the assembly. Since the detector box is made out of acrylic, we needed to test a few things. First, we tested whether TMB attacks acrylic by placing some TMB in acrylic cuvettes and observing them after some time. We used a microscope to examine the inside surfaces of the cuvettes after long exposure to TMB. We found that it may leave a precipitate on the inside surface of an acrylic vessel, and may eat away at least some of the acrylic. For our short-term prototype, the acrylic should be fine, but more research must be done to determine whether acrylic and TMB will be an acceptable combination for the real neutron veto.

We also found that the TMB wicks out and dissolves the wavelength shifting fluor in the fibers if a cut end of the fiber is exposed to the TMB containing liquid. This means that we have to be extremely careful not to break the fibers in an area that will be exposed to TMB, or we risk the integrity of the entire fiber. The four fibers broken during assembly may be compromised when TMB is added to the box.

TMB is also flammable and reactive with water or water vapor in the air. For this reason and for keeping vapor from condensating on the cold SiPMs, the secondary containment box is fitted with a nitrogen purge.

We tested TMB's effect on multiple glues, which were candidates for holding the fibers in place and holding the reflector to the acrylic. We put a sample of each glue in the bottom of a cuvette and filled the cuvettes with the LAB/TMB mixture. We then tested the samples each day for a few weeks in a spectrophotometer to determine whether the glue discolored the TMB solution. We found that 5 Minute Epoxy is compatible with TMB, but RTV epoxy is not. Five-minute epoxy was thus used to glue the reflector to the inside of the acrylic box.

VII. CONCLUSION

In conclusion, we found that SiPMs should be run at the lowest temperature possible that does not affect the electronics in order to increase gain and reduce dark noise. SiPMs are a viable alternative to PMTs for the veto because they are approximately linear in the range of interest and can be made to have the required gain by varying temperature and bias voltage. We found that the best scintillation cocktail for the purposes of the veto is 2g/L PPO and 6.5 mg/L bis-MSB in LAB, with 30% TMB for neutron capture. The acrylic must be very precisely machined to create straight edges which can be welded together tightly with the water-thin acrylic solvent.

VIII. FURTHER RESEARCH

Some further research that must be done includes testing the prototype with a radiation source to see whether the scintillator will react as expected. The TMB still has to be added to the prototype, and its reaction to a neutron source must be observed. Also, other options for safer neutron-capturing compounds to replace the TMB could be investigated.

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